Renewable Energy xxx (2014) 1–7

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Hydrogen supplement co-combustion with diesel in compression ignition engine

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ARTICLE INFO

Article history:
Received 20 May 2014
Accepted 7 August 2014
Available online xxx

Keywords:
Hydrogen supplement combustion
Compression ignition engine
Dual fuel engine
NO_x
Particulate matter and gaseous emissions

ABSTRACT

The present work investigates experimentally the behavior of compression ignition engine while boosting the combustion by enriching air-intake manifold with hydrogen supplement at the atmospheric condition. The study reports the engine thermal efficiency, NO_x emissions and engine exhaust temperature while varying hydrogen content, engine speed and ignition timing. The results show that thermal efficiency of the compression ignition engine increases as hydrogen content increases in the air-intake manifold for the same diesel mass flow rate. The effect of hydrogen supplement on engine efficiency is more pronounced at low engine speed and part-load. The hydrogen supplement causes an increase in NO_x emissions which is attributed to the increase in the combustion temperature and as a result, lower smoke opacity numbers are attained.

1. Introduction

Liquid diesel originating from crude oil is the most common fuel used in compression ignition engines. The recent price climbs of crude oil products has led scientists and engineers to explore the use of alternative possible fuels to run compression ignition engines such as LGP [1] and hydrogen [2,3], in order to replace diesel or at least reduce its use as a fuel for engines. The use of hydrogen in diesel engines is driven by multiple reasons [2] which are (1) increases the hydrogen to carbon ratio of the entire fuel supplied to the engine, (2) injecting small amounts of hydrogen into a diesel engine can decrease the heterogeneity of diesel fuel spray, and (3) reduces the combustion duration. Stoichiometric hydrogen air mixture burns seven times faster than the corresponding gasoline air mixture [4]. This gives great advantage to internal combustion engines, leading to higher engine speeds and greater thermal efficiency [4]. The high heating value and clean burning characteristic of hydrogen make hydrogen one of the most promising alternative fuels that can play great role in replacing fossil fuels.

The use of hydrogen as a fuel in spark ignition (SI) engine [5] has showed a significant reduction in power output. In addition, at high load, pre ignition, backfire and knocking problems have been reported. Hence these problems have limited the use of hydrogen in SI engine [6,7]. Recent work [8] showed that hydrogen-gasoline blend can boost SI engine performance. These contradicting conclusions indicate that more research work is needed to further clarify the features and benefits of hydrogen as a fuel for SI engines.

On the other hand, the use of hydrogen in compression ignition (CI) engines [9] has showed a significant increase in thermal efficiency (by 20%) when compared to pure diesel combustion and an increase of 13% in NO_x emission. Hydrogen fuel cannot be used as a sole fuel in a compression ignition engine, since the compression temperature is not enough to initiate the combustion due to its high self-ignition temperature [9]. Therefore, hydrogen is used as dual fuel and co-combusted in the presence of diesel. In the dual fuel engine arrangement, the diesel fuel is used as the main fuel to initiate the ignition and combustion process while hydrogen is introduced as supplementary fuel through the air-intake manifold or directly injected into the engine cylinders. Hence, major energy is obtained from diesel while the rest of the energy is supplied by the hydrogen. With compression ratio of 24.5, Masood et al. [10] reported an increase of 30% in brake thermal efficiency when hydrogen is co-combusted in the presence of diesel fuel. Lee et al. [7] has reported an increase in thermal efficiency of 22% for dual injection at low loads and 5% at high loads compared to direct injection. Lee et al. [7] studied the dual engine performance of hydrogen-diesel fuel while introducing the fuel solenoid in-cylinder injection and external fuel injection technique. Lee et al. [11] concluded that for dual injection the stability and maximum power are accomplished by direct injection of hydrogen. Das [12] reported experimental results on continuous carburation, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection in which he showed that the maximum

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http://dx.doi.org/10.1016/j.renene.2014.08.019
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Nomenclature

CI	compression ignition
LHV	lower heating value, MJ/kg
LPG	liquefied petroleum gas
LPM	liter per minute
$\dot{m}$	mass flow rate, kg/s
PM	particulate matter
$\dot{Q}$	heat rate, kW
SI	spark ignition
sfc	specific fuel consumption, kgN.m
T	torque, N.m
$\dot{W}$	power, kW
Greek symbols	
η	thermal efficiency
ω	angular velocity, Rad/s
Subscripts	
in	input
out	output

brake thermal efficiency of 31.3% is obtained at 2200 RPM with 13 N-m torque.

The use of hydrogen fuel, as a potential supplement fuel to reduce the use of liquid diesel fuel, comes with a drawback of increasing NO_x emission. Thus the need for techniques to reduce NO_x becomes more vital for engines operating with dual hydrogen-diesel fuel. One common method to reduce NO_x emission in diesel engine is by injecting steam to the combustion [13]. Another way to reduce NO_x is by operating the engine with lean mixtures. Lean mixture results in lower temperature that would slow the chemical reaction, which weakens the kinetics of NO_x formation [14,15].

One of the main advantages of hydrogen combustion over diesel fuel is that it does not produce major pollutants such as hydrocarbon (HC), carbon monoxide (CO), sulfur dioxide (SO_2), smoke, particulate matter, lead, and other carcinogenic compounds. This is due to the fact that it is only water what comes out of the complete hydrogen combustion in air, in addition of course to the generated NO_x due to the presence of Nitrogen in the air [16]. So, the hydrogen-operated engines' main disadvantage is the NO_x emissions. Under the clearly high combustion temperatures, supported further by the combustion of the Hydrogen in the overall fuel supplied to the engine, the nitrogen present in the air reacts with oxygen to form NO_x. A recent study [3] showed that hydrogen fuel supplement can be used in diesel engine with hydrogen to diesel ratio of 34% calculated based on amount of energy in the fuel (which represent 19% as mass ratio between hydrogen to diesel).

This study addresses the advantage of using hydrogen supplement in diesel engine while at the same time pointing the effect of hydrogen on emission. The hydrogen is introduced through the air-intake manifold at atmosphere condition to assure minimal retrofit to current diesel engine. The supplement hydrogen can be produced using renewable source of energy such as solar energy with water electrolysis.

Utilizing dual fuel configuration, this study reports the effect of hydrogen supplement fuel that is injected to the air-intake manifold of a compression ignition engine and co-combusted in the presence of diesel fuel where diesel is combusted as the main fuel. The hydrogen supplement is used to replace a portion of the diesel fuel required to produce the engine output power. The study reports the effect of hydrogen supplement fuel on the engine efficiency, specific fuel consumption, exhaust temperature, NO_x emission and PM emission.

2. Experimental setup

A schematic diagram of the engine with instrumentations is show in Fig. 1. The test is conducted using a Ricardo E6 research engine which is a single cylinder compression ignition engine. The engine is fully equipped with instrumentation for measurements of all engine operating parameters. The engine is modified to work with hydrogen in the dual fuel mode where hydrogen is injected into the air-intake manifold as shown in Fig. 1. The engine is loaded by an electrical dynamometer rated at 22 kW and 420 V. The torque of the engine is measured through force transducer that is connected to the electrical dynamometer which has uncertainty of ± 0.1 N. The liquid fuel flow rate is measured digitally by a multi-function microprocessor-based fuel system. The engine specifications are shown in Table 1. The chemical characteristics of the primary fuel (diesel) and the supplement fuel (hydrogen) are listed in Table 2.

As shown in Fig. 1, hydrogen gas is injected into the air-intake manifold at atmosphere pressure. A pressure regulator, a volumetric rotameter and a throttle value are used to control the hydrogen flow rate. The uncertainty of the hydrogen flow meter is ± 0.5 LPM. The flow rate of air is measured using a calibrated orifice meter with pressure transducer arrangement. The pressure transducer has uncertainty of ± 0.1 Pa. The diesel flow rate is measured by recording the required time to consume a fixed volume of diesel with uncertainty of ± 0.1 ml/s. The measurement of combustion pressure, engine speed, engine output torque, and crank angle are collected using a high speed data acquisition system. A labVIEW interface program has been written to collect the data at a rate of 50,000 points per second and to store the data.

The main objective of the conducted experiments is to understand the effect of hydrogen supplement on the performance of a dual fuel single cylinder diesel engine under different conditions, hence three sets of tests have been conducted which are as follow:

1) Test the effect of 4 LPM hydrogen when combusted with diesel engine in dual mode while varying engine speed from 1080 RPM to 1800 RPM.
2) Test the effect of variable hydrogen flow rate at fixed engine speed. The hydrogen flow rate is varied from 0 to 8 LPM insteps of 2 LPM for fixed engine speed of 1260 RPM.
3) Test the effect of varying injection timing while engine is running in dual mode with hydrogen flow rate of 4 LPM, at fixed engine speed of 1260 RPM.

The engine efficiency and specific fuel consumption are calculated using equations (1) and (2) respectively:

$$\eta = \frac{\dot{W}_{\text{out}}}{\dot{Q}_{\text{in}}} = \frac{T \cdot \omega}{(\dot{m} \times \text{LHV})_{\text{Diesel}} + (\dot{m} \times \text{LHV})_{H_2}} \quad (1)$$

$$\text{sfc} = \frac{\dot{m}_{\text{fuel}}}{\dot{W}_{\text{out}}} \quad (2)$$

$$\dot{m}_{\text{fuel}} = (\dot{m})_{\text{Diesel}} + (\dot{m})_{H_2} \quad (3)$$

The lower heating value is used in equation (1) for the efficiency calculation since no vapor is condensed during the experiment. The density of hydrogen is calculated at the air-intake condition; namely at atmosphere pressure and room temperature.

The exhaust emission is measured using VARIO plus SE instrumentation manufactured by MRU Instruments, Inc. The analyzer

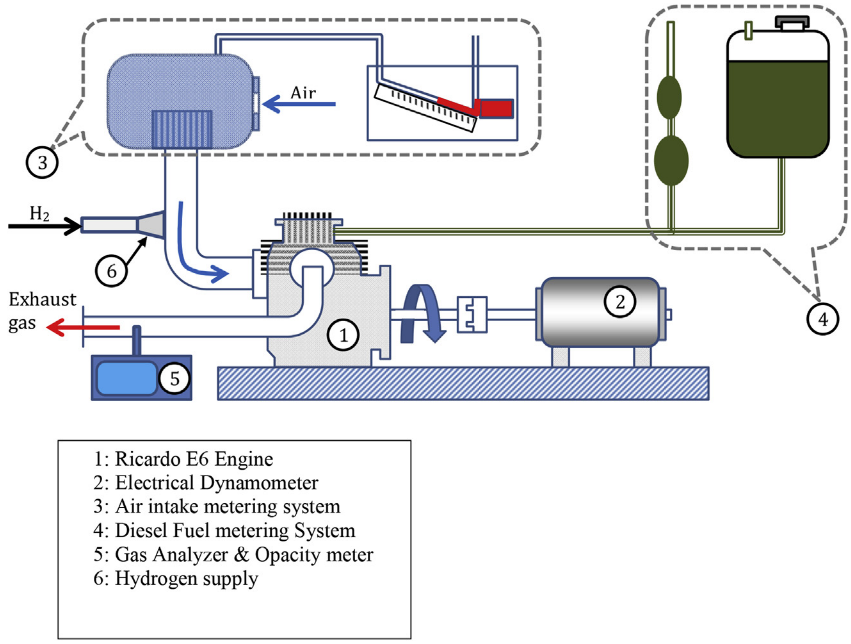

Fig. 1. Schematic view of the engine test bed: (1) engine, (2) dynamometer, (3) air intake system with drum tank and inclined manometer, (4) fuel system with fuel tank and flow measuring volume, (5) strain gauge load cell sensor for torque measurement, (6) pressure transducer, (7) emission monitoring systems, and (8) Hydrogen inlet to the air intake manifold.

uses electrochemical sensors to measure the gas component concentrations in flue gases with accuracy of ±5 ppm for NO_x. The unit is calibrated with regular air before start recording any measurements.

The opacity is measured using AVL Opacimeter which is a dynamic partial-flow measuring instrument for the continuous measurement of exhaust gas opacity. A measuring chamber of defined measuring length and non-reflecting surface is filled homogeneously with the exhaust gas. The loss of light intensity between a light source and a receiver is measured and from it the opacity of the exhaust gas is calculated. The calculation is based on the Beer–Lambert law.

3. Results and discussion

The effect of hydrogen supplement on diesel engine performance is investigated under different testing conditions which are as follow:

3.1. Effect of engine speed.
3.2. Effect of hydrogen flow rate.
3.3. Effect of injection timing.

3.1. Effect of engine speed

The effect of hydrogen addition is investigated under variable engine speed (1080 RPM to 1800 RPM) and is compared against base-case study for pure diesel. The results under variable engine speed are shown in Fig. 2 where diesel is injected at 35° from btdc. As shown in Fig. 2a, the thermal efficiency increases as engine speed increases and then drop after reaching an optimum value. The behavior is Fig. 2a is expected since at the beginning, the increase in the engine speed leads to upsurge in the turbulence levels that leads to better mixing and to more intense smoother combustion. Then an optimum is reached, then any further increase in the engine speed leads to just a reduction in the volumetric efficiency due to limitations in the breathing ability of the engine cylinder and the high opening/closing frequency of the intake valves and the associated difficulty and complexity of the air suction process. Further increase of the engine speed decreases the volumetric efficiency and power output, hence it leads to fall in the thermal efficiency. The combustion with hydrogen supplement shows better efficiency when compared to pure diesel case. This is expected since hydrogen has higher flame temperature and faster flame speed when compared to the pure diesel combustion. The specific fuel consumption is shown in Fig. 2b and as the results show, the presence of hydrogen reduces the specific fuel consumption since the lower heating value (LHV) of hydrogen is two and half times higher than diesel and the effect is more pronounced at part load (low engine speed).

As shown in Fig. 2c, the exhaust temperature is higher in the presence of hydrogen when compared to pure diesel case. The

Table 1
Ricardo E6 Engine specifications.

Number of cylinders	1
Bore	76.2 mm
Stroke	111.1 mm
Swept volume	0.507 L
Max. speed	50 rev/s (3000 RPM)
Max. power, diesel (CR = 20.93)	9.0 kW, naturally aspirated
Compression ratio (CR)	Max. CR 22
Injection timing	Variable, 20°–45° btdc

Table 2
Fuel properties.

Fuel property	Diesel	Hydrogen
Chemical formula	$\approx C_{12}H_{26}$	H_2
Density, kg/m^3	815	0.08988
Molecular weight, kg/kmol	170	2.016
Lower heating value, MJ/kg	42.5	119.96
Stoichiometric air–fuel ratio, kg/kg	14.5	34.3
Ignition temperature, °C	355	500
Adiabatic flame temperature, °C	1720	2210
Sulfur content by weight, %	0.5	0

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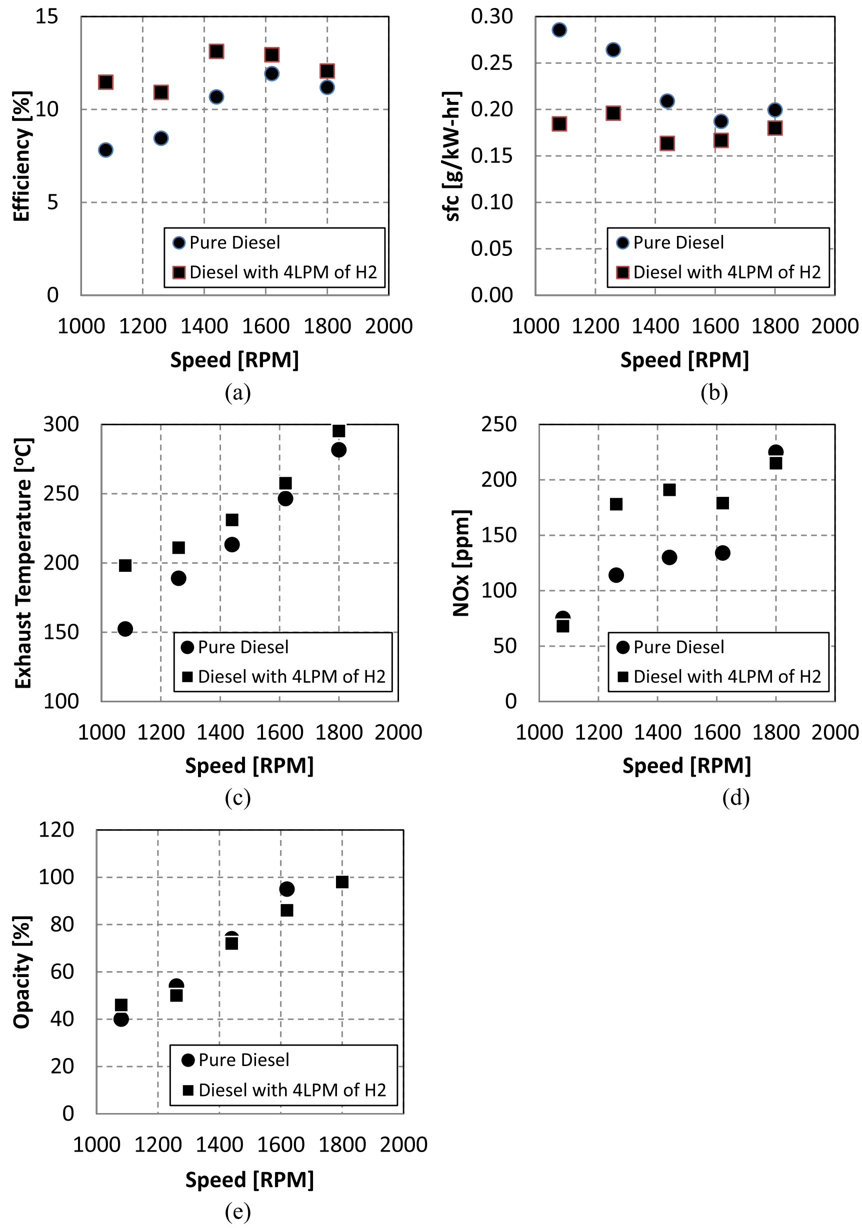

Fig. 2. The effect of engine speed with the presence of 4 LPM of hydrogen supplement, where diesel is injected at 35° from btdc, on (a) engine efficiency, (b) specific fuel consumption, (c) exhaust gases temperature, (d) NO_x emission and (e) engine opacity.

increase in exhaust temperature is due to (a) the high heating value of hydrogen when compared to diesel and (b) the high flame temperature when compared to diesel. Since it is difficult to measure the flame temperature inside the internal combustion engine, the exhaust temperature is used as an indicator to the flame temperature. Hence a higher exhaust temperature means a higher flame temperature. As shown in Fig. 2d a high flame temperature will produce more NO_x. The NO_x is produced during the combustion process when nitrogen and oxygen are present at elevated temperatures.

For solid particulates matter emissions, a direct correlation with the exhaust gas opacity (in percentage) is used to reflect qualitatively the PM emissions levels. Increasing the engine speed leads to a shorter residence times in the combustion chamber with less fuel air mixing which leads to higher smoke in the exhaust hence opacity increases. The PM emissions are shown in Fig. 2e. The higher the combustion temperature with hydrogen supplement, the higher the NO_x emissions and the lower the PM emissions compared to pure diesel. Increasing the hydrogen addition enhances the premixed flame combustion and leads to a higher combustion temperature which tends to decrease the formation of unburned carbon in the exhaust.

3.2. *Effect of hydrogen flow rate*

The effect of amount of hydrogen supplement when it is burned with diesel is shown in Fig. 3 where diesel is injected at 35° from btdc. For current engine, the results show that as hydrogen supplement increases the engine efficiency increases which is expected since hydrogen presence will upsurge the combustion temperature and enhances mixing due to the fact that flame move faster in hydrogen when compared to diesel. As shown in Fig. 3a and for engine speed of 1260 RPM, the thermal efficiency increases with the increase of hydrogen flow rate from 0 to 8 LPM. The

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specific fuel consumption for fixed engine speed of 1260 RPM and different hydrogen flow rate is shown in Fig. 3b and it is clear that as hydrogen flow rate increases that the specific fuel consumption decreases. This reduction in sfc is expected since the lower heating value (LHV) of hydrogen is two and half times higher than LHV of diesel.

The temperature of the exhaust gases with respect to hydrogen flow rate is shown in Fig. 3c. As expected the increase of hydrogen supplement fuel will cause rise in the flame temperature and hence in the exhaust gases temperature. The increase in combustion temperature tends to increase NO_x emission, as shown in Fig. 3d, since NO_x is produced when nitrogen and oxygen are present at elevated temperatures.

The increase in the combustion temperature and increase in the NO_x are associated with a decrease in the exhaust opacity from 54% at 0% hydrogen to 40% at 2 LPM, as may be seen in Fig. 3e. As hydrogen is admitted with the intake air, further hydrogen addition tends to reduce the air admitted to the engine which tends to decrease the NO_x formation as seen in Fig. 3d and increases in the smoke formation as seen in Fig. 3e.

3.3. Effect of injection timing

The effects of diesel fuel injection timing on engine performance while being supported with hydrogen supplement are shown in Fig. 4. As shown in Fig. 4a, at engine speed of 1260 RPM with hydrogen supplement of 4LPM, the engine efficiency decreases with the advance in injection timing (early injection) from 20° to 40° btdc. Early injection will cause too much pressure rise before end of compression stroke which reduces output power and hence reduces engine efficiency. The specific fuel consumption for fixed engine speed of 1260 RPM and flow of 4 LPM of hydrogen supplement fuel is shown in Fig. 3b. The specific fuel consumption increases as injection timing is advanced since as stated earlier advancing injection timing will reduce output power.

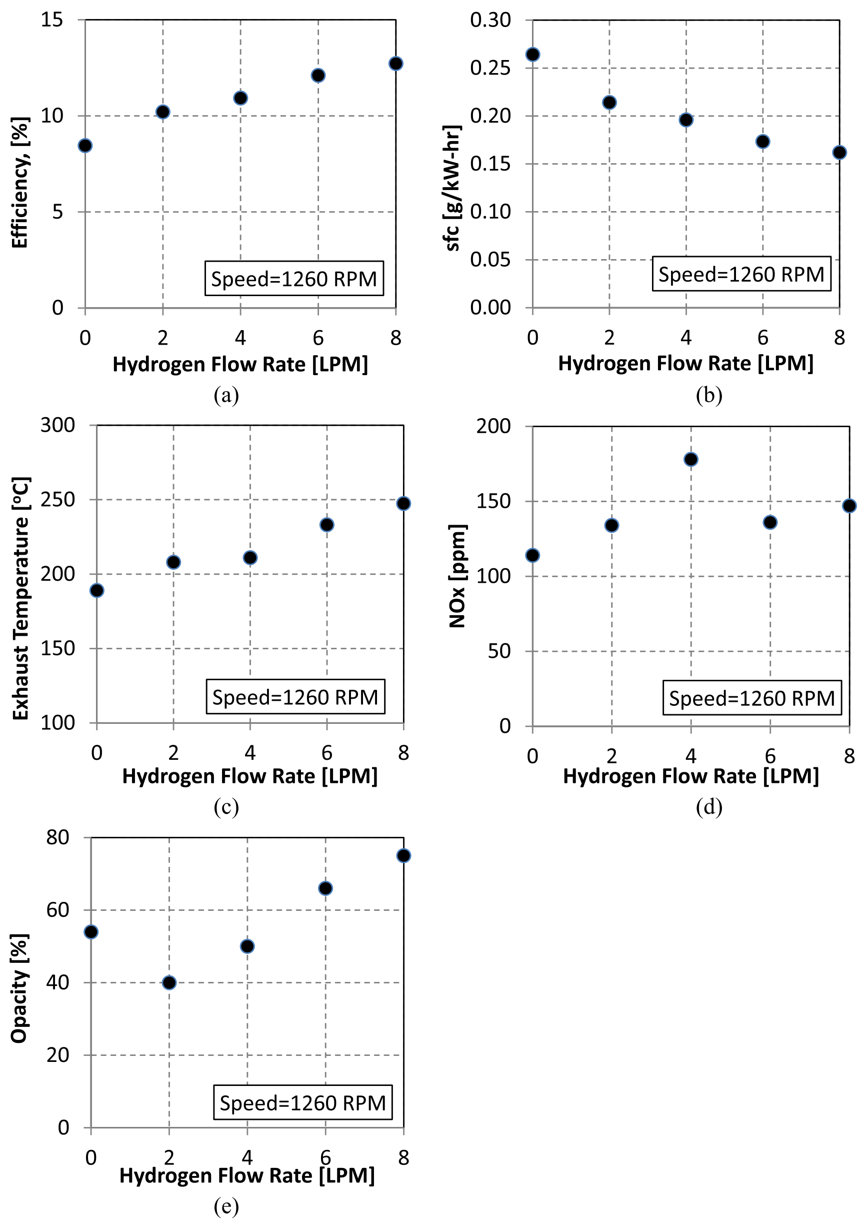

Fig. 3. The effect of hydrogen supplement flow rate fixed engine speed of 1260 RPM, where diesel is injected at 35° from btdc, on (a) engine efficiency, (b) specific fuel consumption, (c) exhaust gases temperature, (d) NO_x emission and (e) engine opacity.

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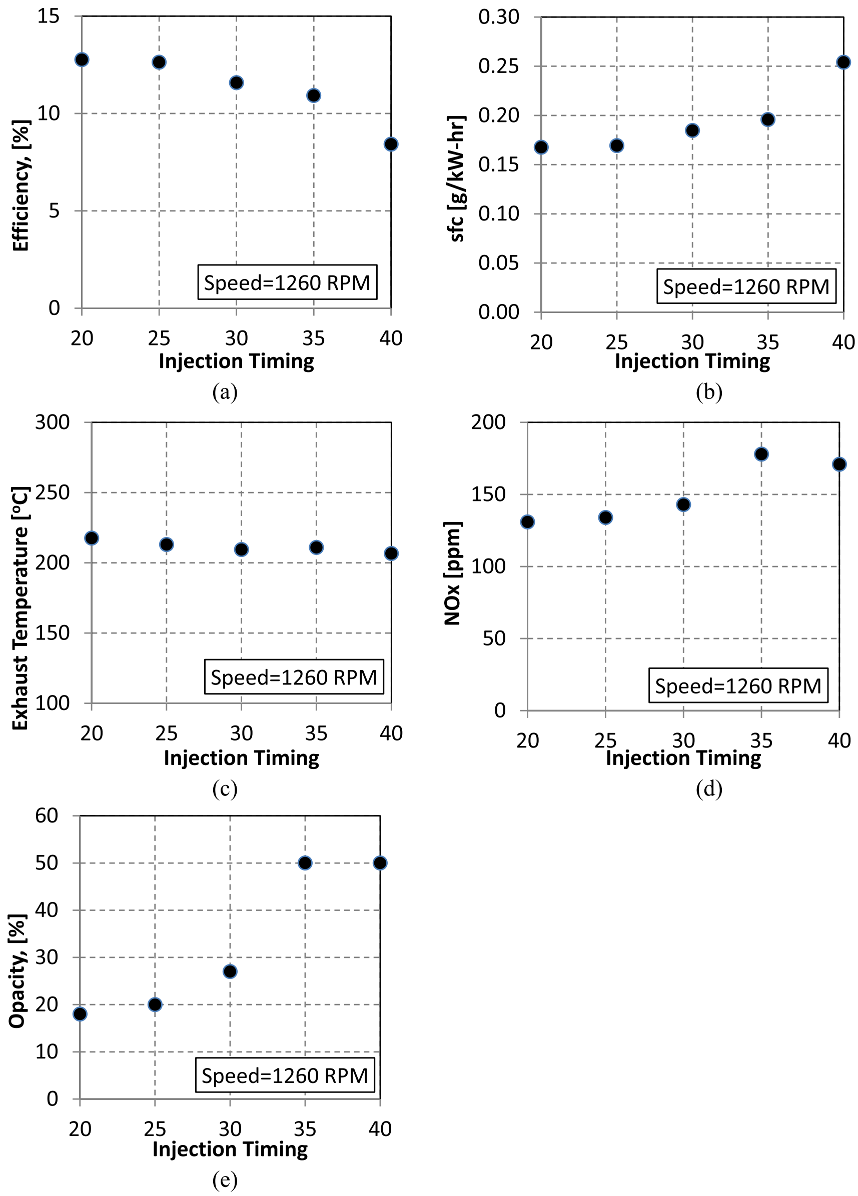

Fig. 4. The early diesel injection timing with the presence of 4 LPM of hydrogen supplement on (a) engine efficiency, (b) specific fuel consumption, (c) exhaust gases temperature, (d) NO_x emission and (e) engine opacity.

The effect of early injection on exhaust temperature is limited to a small decrease due to the reduction in the temperature at the end of expansion stroke, which is observed in Fig. 4c. The engine NO_x emission is shown in Fig. 3d which shows that as injection timing is advanced, the NO_x increases which is due to the high rise in the peak temperature and pressure of the engine during the compression stroke. As the injection timing becomes more advanced, the pressure and temperature at time of injection becomes less and less. This tends to increase the delay period of the diesel fuel and hence more mass of fuel is being injected without burning. This tends to increase the smoke formation in the exhaust as shown in Fig. 4e.

4. Conclusions

In this work, an experimental investigation has been conducted to examine the effect of the presence of hydrogen supplement on the performance of dual fuel diesel engine. The hydrogen is introduced to the engine at atmospheric conditions by injecting the hydrogen to the air-intake manifold. It is found that the presence of 4 LPM hydrogen supplement boosts the engine efficiency for engine speed range of 1080 RPM to 1800 RPM. Also the engine efficiency at engine speed of 1260 RPM keeps increasing with the increase of hydrogen supplement flow rate. The engine run smoothly with the presence of hydrogen and no knocking is detecting during above testing conditions. In parallel to the thermal efficiency boosting, the results demonstrate an increase in NO_x Emissions and lowering in particulate matter formation.

Acknowledgments

The authors would like to acknowledge the support provided by United Arab Emirates University. This work is financially supported by the College of Engineering at the United Arab Emirates University.

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